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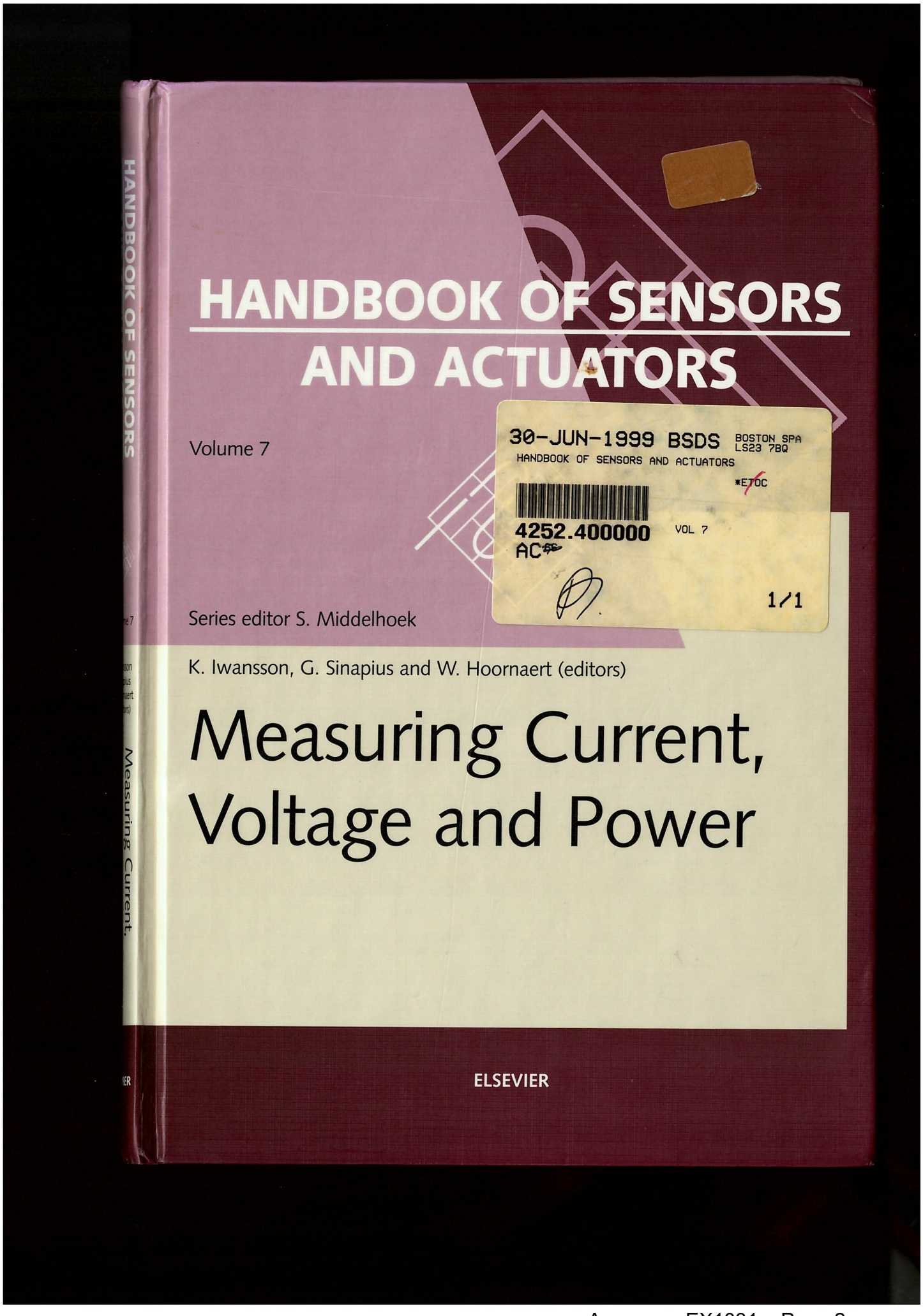
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SUMMARY

This authoritative new book focuses on recent developments in the instrumentation for sensing voltages and currents. It covers new trends and challenges in the field, such as measurements of biocurrents, the increased speed of the components for data taking, testing of computers and integrated circuits where the measurement of rapid voltage and current variations on a very small geometrical scale is necessary. The first chapter concentrates on recent methods to sense voltages and currents, while the rest of the book investigates the applied side, covering for instance electrical power and energy measurements. The main purpose of this volume is to illustrate commonly employed techniques rather than track the scientific evolution and merits and therefore mainly covers patent literature aimed at industrial applications. It is an exciting addition, justifying the series' claim to cover state-of-the-art developments in both the applied and theoretical fields of sensors and actuators.

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CHAPTER 1

SENSORS AND TRANSDUCERS

1.0 INTRODUCTION

To measure voltages or currents one usually exploits observable effects related to these variables (e.g. the deflection of the needle of a galvanometer). Galvanometers date from the discovery of the interaction between an electric current and a magnetic needle by Oersted in 1819. Galvanometers made accurate analogue current measurements possible. Due to the lack of comparable devices for voltage measurements, for a long time voltage measurements have been done as current measurements. For digital measurements the contrary is true. The analog-to-digital voltage converter (ADC) is the most commonly used analog-to-digital interface. Thus, most digital current measurements are done as voltage measurements.

A number of devices are employed to transform the voltage or current to be measured into a form suitable for further processing. In the first place there are voltage/current dividers and measuring amplifiers. A second group of devices transform an input variable into another variable. These we call sensors. This chapter deals with commonly used sensors and effects related to the voltage or current to be measured. The distinction between measuring circuits and sensors is not always easy. Bridge arrangements, like the Wheatstone-bridge, will not be covered.

The choice of the sensor depends on the variable to be sensed and the response required. The response of the sensor may be for example a voltage or a current within a predetermined range of values relative to/at a chosen potential or a change of polarisation of polarised light. Depending on the physical effect involved, the response can e.g. be linear (Pockels) or quadratic (Kerr). Arrangements with compensation decrease the sensitivity to distortions in the response and increase both, the measuring range and the resolution. A variable that can be measured more easily, e.g. a reference, is applied to the sensor to compensate for the effect due to the variable to be sensed and the sensor is used as a comparator to detect when the compensating variable equals the variable to be measured.

The different kinds of sensors can be grouped into two categories: contacting and contactless. The output from contactless sensors is galvanically isolated from the source of the signal. Usually contactless sensors affect the variable to be measured less. Due to the less direct nature of the measurement, however, precision may also be less. Fiberoptic sensors, made from crystals and optical fibres only, offer the advantage that they are less sensitive to electric and magnetic stray fields than sensors containing electronic circuitry.

For most sensors estimates for their sensitivities have been given. Due to the numerical uncertainty of the experimental data, a lack of detail concerning some experimental parameters and the bias of "typical results" the respective values represent order of magnitude estimates. In those cases where some numerical values necessary for these estimates have not been indicated in the respective publications, whenever possible these values have been taken from a physics textbook [1].

In this book SI units are used unless explicitly otherwise stated.

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1.1 VOLTAGE SENSORS

1.1.1 Overview

The range of voltages to be measured ranges from several kV in gas-insulated power installations to mV on electrostatically charged surfaces. Voltage sources in power lines have considerable current sourcing capabilities over long periods of time; electrostatic charged surfaces deliver short current pulses only. For the testing of integrated circuits one has to measure MHz voltage signals with µm spatial resolution.

Measuring the voltage at a point P_1 one determines the electric potential difference U with respect to a reference point P_2, e.g. ground. The potential difference between two points P_1 and P_2 corresponds to the line integral of the electric field E along any path s that connects these points:

$$U = -\int_{P_1}^{P_2} \vec{E}\, d\vec{s} \qquad (1)$$

When P_1 and P_2 are connected by an electrical conductor (having a resistance R) and a current source is provided, a current flows; its magnitude is determined by Ohm's law.

The most common way to measure a voltage U_S between two points is to connect them through a (high) resistance R and a galvanometer (with a combined resistance R_M) and to measure the current through there. When a current flows, however, the output resistance of the voltage source, R_S, and its current sourcing capability have to be taken into account. The voltage drop, U_M, across R and the galvanometer is related to the voltage U_S by:

$$U_M = \frac{R_M}{R_M + R_S} U_S \qquad (2)$$

The measurement error, i.e. the difference between U_M and U_S decreases with increasing R_M which implies that in such a measurement very low currents have to be measured with high accuracy. Limitations due to the current sourcing capability of the voltage source can be overcome with a feedback arrangement. In such a circuit a compensating current is provided to cancel the current from the source. The voltage is then obtained from the measured compensating current and the values of the resistors involved.

If the points P_1 and P_2 are not connected by an ohmic resistance but by a capacitor which is disconnected after an appropriate period of time, the DC voltage between these points can be derived from the charge stored in the capacitor (cf. Equ. 5). With a circuit, in which the capacitor is disconnected from the points P_1 and P_2 before the voltage measurement, voltages at an arbitrary potential with respect to the measurement circuit can be measured [2]. The charge stored in the capacitor can be determined by any suitable method, e.g. by connecting it to a constant current source and measuring the time of discharge [3].

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Voltage can be measured directly with electronic valves or transistors which for a unipolar voltage act as amplifiers with a very high input resistance, cf. Section 1.1.2. More recently Josephson junctions have been used for DC voltage measurements, cf. Section 1.1.3.

The methods described thus far use contacting sensors. A sensor, e.g. a galvanometer, is conductively connected to both, the point whose potential is to be measured and the reference point. A contactless probe that transforms the voltage at P_1 into another electrical variable does not have an ohmic contact with that point. To measure a current related quantity, e.g. a displacement current with a capacitive probe (Section 1.1.4), the probe must still be connected to the reference point. The same holds for the anode in field emission or secondary electron probes (Section 1.1.5). In the latter case not the current but the field dependent energy of the electrons is measured to determine a voltage.

A complementary method to measure the voltage between two points consists in sensing the associated electrical field instead of a current. For this purpose all electric field sensors can be used. Sections 1.1.6 to 1.1.8 cover probes for electric field related phenomena other than current. Section 1.1.6 covers electrometers. Sensors made from materials whose optical or mechanical properties depend on the electric field are treated in Sections 1.1.7 and 1.1.8. These sensors are contactless, they do not require conductive connections to either of the two points whose potential difference is to be sensed.

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1.1.2 Transistors

Nowadays transistors (bipolar or FETs) have taken over from electronic valves in most voltage measurements. The voltage to be sensed is connected to the base and the emitter (gate and source). If the voltage has the correct polarity and magnitude, a collector (drain) current flows. With a single transistor unipolar voltages from DC up to high frequencies can be sensed. The finite base resistance of bipolar transistors (megohms) is the main disadvantage compared to electronic valves. These transistors act as high resistance current amplifiers. FETs do not have this drawback because their gate resistance is orders of magnitude higher.

Transistors used as voltage sensors provide a collector (drain) current whose magnitude is a function of the voltage applied. With a symmetric arrangement of the transistors such circuits are suited for bipolar voltage signals. If the transistor in the circuit is configured as an emitter(source) follower, the voltage drop over the emitter (source) resistor equals the input base (gate) voltage. The output resistance of the circuit is much lower then its input resistance because the transistor acts as an impedance transformer.

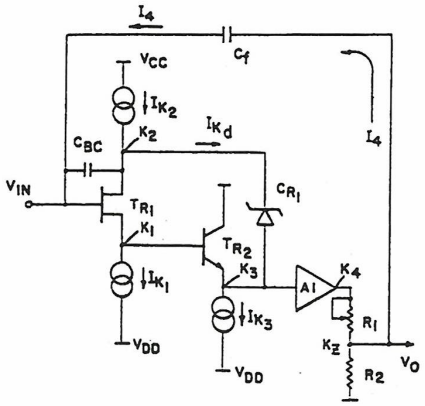


Figure 1 [4]

Circuit for High Impedance Broad Band Probe

C_{BE} is small because the gain K_1 at the emitter is almost 1 for an emitter follower. In order to minimise C_{BC}, the gain K_2 is tied to a value close to K_1 by the Zehner diode CR_1 which (for AC) couples the collector to the emitter. The transistor TR_2 provides a current I_{K3} to make the current I_{K1} equal to the current I_{K2}. C_{BS} is reduced by the mechanical design of the circuit. Due to the current I_4 the capacitance C_f acts as a "negative impedance", i.e. it can be used to compensate the remaining capacitances.

When high frequency signals are to be measured, the internal capacitances of the transistors may cause problems. The input capacitance C_{ip}, of the circuit shown in Figure 1 [4] depends on the base-to-substrate capacitance, C_{BS}, the base-to-emitter capacitance, C_{BE}, and the base-to-collector capacitance, C_{BC}, and is further influenced by the Miller effect, which describes the increase of the base-to-collector capacitance and which gives rise to a multiplicative factor (1 - K), where K is the gain of the transistor:

$$C_{ip} = C_{BS} + C_{BE} + C_{BC}\,(1 - K) \qquad (3)$$

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Each capacitance C_{BX} in Equ. 3 represents an effective capacitance, the value of which, due to the Miller effect, is given by the product of the mechanical capacitance and the term $(1 - K_X)$, where K_X is the gain measured at the respective terminal X of the transistor TR_1.

If one only wants to know whether a voltage exceeds a reference value, one may use a differential amplifier (comparator). The main components of these devices are bipolar transistors. They provide a binary output, i.e. their output voltage is at one of two levels depending on which of the two input voltages is higher. The operation of ADCs consists of multiple voltage comparisons, either in parallel or sequential (successive and single/dual slope type).

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1.1.3 Josephson Junctions

When two superconductors are coupled through a small tunnelling barrier, special (Josephson) effects occur. In this section we are only concerned with the AC Josephson effect, further applications of the Josephson junctions are discussed in Section 1.2.12.

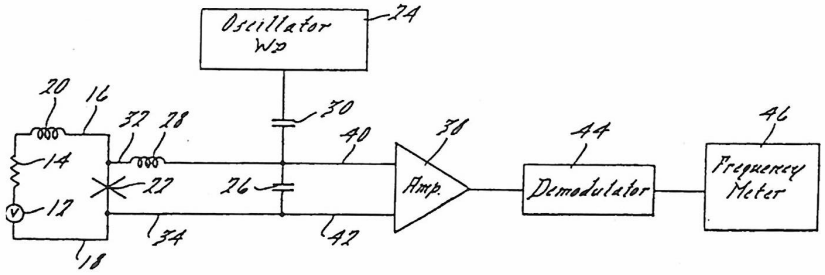


Figure 2 [5]

Superconducting Circuit Means

Superconducting leads (16, 18) couple a voltage source (12) with an internal resistance (14) to the Josephson junction (22). The Josephson junction is chosen such that its critical current $i_e = \Phi_0/L$ is about 10^{-5} A, where L is the magnitude of the inductance (20) of the superconducting leads. Capacitor (26) and inductance (28) form a resonance circuit whose resonance frequency is matched to the frequency f_{osc} of the RF oscillator (24). Junction (22) mixes the frequencies f and f_{osc} to provide two sidebands $f_{osc} \pm f$ and acts as parametric amplifier. After demodulation f is applied to a frequency meter. With this circuit a measurement of $4 \cdot 10^{-16}$ V with a S/N of 10 has been achieved with a source resistance of 10^{-10} Ohms at 4.2 °K.

When a current greater than the critical current is driven through a Josephson junction, a DC voltage U appears across that junction. This voltage in turn gives rise to a supercurrent that oscillates with a frequency f:

$$f = \frac{U}{\Phi_o} \tag{4}$$

Φ_o is the magnetic flux quantum associated with a Cooper pair, its value is $2 \cdot 10^{-15}$ Wb (1 Weber = 1 Vs). With the above equation the voltage to be measured can be derived from the observed frequency. A suitable circuit is shown in Fig. 2 [5].

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1.1.4 Capacitive Sensors

1.1.4.1 DC Voltage

Capacitive sensors are used to measure DC and AC electric fields and voltages. Their field of application ranges from circuit boards to power lines. A capacitive sensor consists of a conductive surface that, together with the sample surface, forms a capacitor. The relation between voltage, U, capacitance, C, and the charge, Q, stored in a capacitor is:

$$Q = U\,C \tag{5}$$

In the simple case of an idealised parallel plate capacitor (having plates with a surface area a, a plate distance d and a capacitance $C = (\varepsilon_0\, a)/d$) the corresponding equation for the electrical field $|E| = U/d$ reads:

$$Q = \varepsilon_o\, |\vec{E}|\, a \tag{6}$$

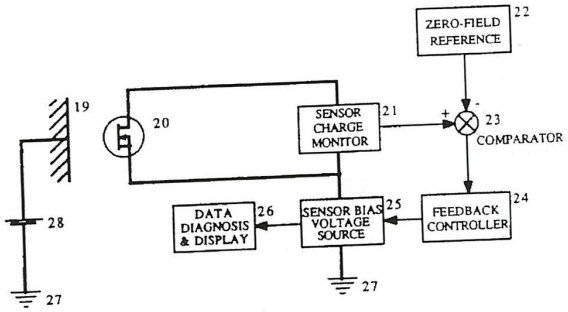


Figure 3 [6]

Potential Analyser

Charge incurred in the sensor (20) by the surface potential of the sample surface (19) alters the impedance of a semiconductor channel within the sensor. The deviation in the charge dependent impedance of the sensor from a calibrated zero-field reference (22) is used by a feedback controller (24) to alter the base potential of the sensor to eliminate the deviation signal. In this state, the surface potential of the sensor matches that of the sample thus forming a zero-field condition, as a result no charge is induced in the sensor. The surface potential difference between the sample and the sensor is then equal to the sensor base voltage, which is directly measured by a voltmeter. Due to the absence of induced charge in the zero-field condition the measurement is independent of the sample/sensor separation (typically < 0.5 mm).

According to Equ. 5 the charge stored on the sensor electrode gives a measure of the voltage. One approach consists in a measurement of this charge. The first instruments used for this purpose were leaf electrometers. Other devices that measure the coulomb force between electrodes are treated in Section 1.1.6. Any other charge measuring method will do as well.

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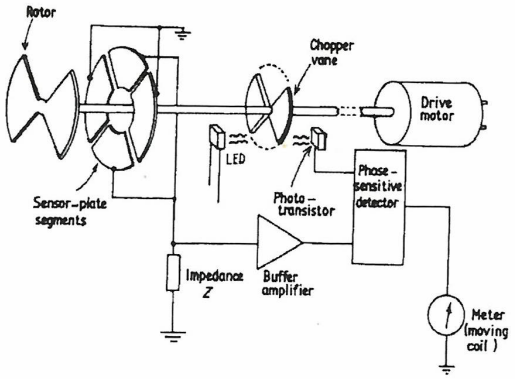


Figure 4 [7]

Schematic Diagram of Field-Mill System with Polarity-Sensing Circuit

A signal representing the rotor position is provided to the phase-sensitive detector. With the phase sensitive detector not only the magnitude but also the polarity of the electric field can be determined.

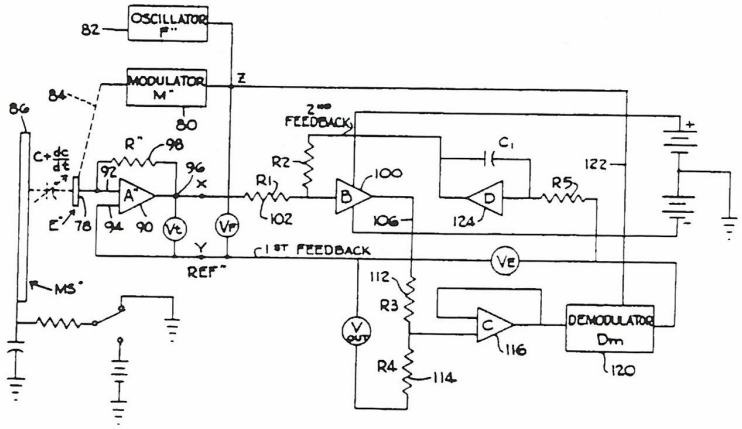


Figure 5 [8]

High Speed DC Non-Contacting Electrostatic Voltage Follower

A vibrating capacitance detector is coupled to a surface containing both wideband electrostatic AC and DC potentials. The detector is connected to the inverting input of detector amplifier (90) the output of which is connected to a high bandwidth amplifier (100). A first feedback path is provided from the high bandwidth amplifier to the non-inverting input of the detector amplifier which provides both, a signal which is equal to and follows the wideband electrostatic AC potentials on the measured surface and a signal at the vibrating capacitance modulation frequency, representative of the DC potential of the measured surface. A second feedback path includes a demodulator (120) and integrator (124, C_1) to monitor the first feedback path and to provide a DC correction signal to the high bandwidth amplifier to null the signal on the first feedback path which is representative of the vibrating capacitance modulation of the DC potential. As a result, the monitored signals on the first feedback path will be driven to follow, and exactly match all wideband AC and DC electrostatic data on the measured surface.

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The field-effect probe of Fig. 3 [6] consists of an unshielded semiconductor similar to a MOSFET. Its conductivity depends on the amount of charge induced. It is operated in a bridge arrangement with a negative feedback to balance the charge.

The second approach avoids the difficulty of charge measurements and uses the time derivative of Equ. 5 or 6 to obtain a resulting current. The field mill in Fig. 4 [7] consists of a rotor that periodically shields the sensor-plate segments (stator) such that an alternating electric field is observed. Alternatively a capacitive probe can be vibrated in a direction normal to the sample surface to cause a variation of the capacitance (and of the electric field). According to Equ. 5 the resulting current is proportional to the DC voltage. Additional AC voltages require special signal treatment, see e.g. Fig. 5 [8].

1.1.4.2 AC Voltage

In the case of alternating voltages or fields the time derivatives of Equ. 5 or 6 have to be used. For sinusoidal signals with a frequency f capacitive sensors act as an impedances with a magnitude of $1/(2\pi f C)$. Following Maxwell's equations the term dE/dt in the time derivative of Equ. 6 is referred to as "displacement current". In the sensor shown in Fig. 6 [9] the insulation of the conductor acts as dielectric of the capacitor. Fig. 7 [10] shows a sensor with a shielded probe for circuit testing. A measurement with such a probe will only moderately affect the operation of the circuit under test. Since the accuracy of the measurement crucially depends on the knowledge of the distance between the probe and the test point, such a probe is better suitable for the measurement of the timing characteristics of signals than for absolute voltage measurements.

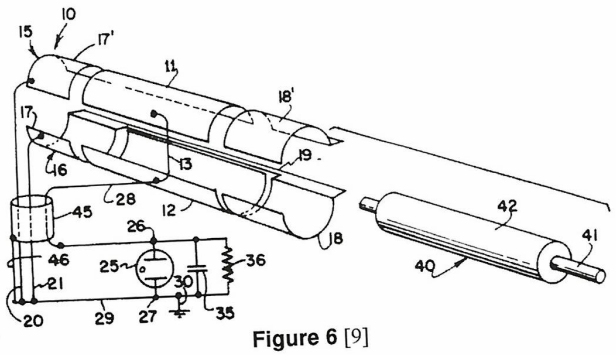


Figure 6 [9]

Capacitive Pickup Device for Pulsating High Voltage Measurements

The device derives a measurable voltage which is a linear function of the magnitude of pulsating high voltage of the order of 15 to 40 kilovolts in an insulated conductor. The pickup device includes a pair of electrically conducting plates (15, 16) , the plates being centrally relieved to accommodate the pickup plate members (11, 12) and adapted to be connected to ground to reduce the influence of fringe fields.

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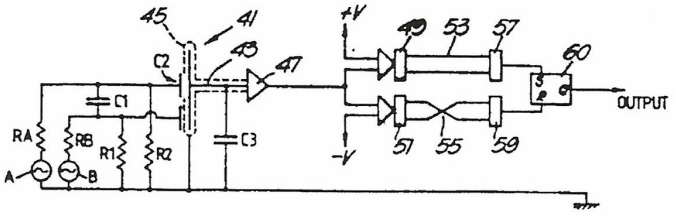


Figure 7 [10]

Electric Circuit Testing Equipment

The shielded probe unit (41) is capacitively coupled to a selected point in the circuit. The signals picked up by the probe unit are conditioned to produce an output signal corresponding only to signals picked up by the unit from the selected point. The conditioning of the signals allows the pick-up of unwanted signals to be tolerated.

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1.1.5 Electron Current Analysers

1.1.5.1 Applications

This section deals with sensors used for **integrated** or **printed circuits**. In circuit **testing** the variable of interest usually is not just a voltage but also the timing characteristic of voltage signals at different locations of the circuit. Thus, a high spatial and temporal resolution is required. These requirements are best met by devices that analyse the electron current emitted from the area of interest.

High spatial resolution can be achieved with tunnel microscope like devices, i.e. with a very fine probe-tip at some distance above the surface of the circuit. The probe current depends on the potential difference between sample and probe-tip. For signal tracing in circuits, rapid scans over the whole circuit area have to be performed. Only particle or laser beam devices meet the speed requirements. The potentials are derived from the energy of the emitted secondary electrons. A comparison of electron beam testers (EBT) and electro-optical testers (cf. Section 1.1.7) shows a superior spatial resolution for EBTs (less than 0.1 µm) whereas for the temporal resolution electro-optical devices do better (about 1 ps) [11].

1.1.5.2 Tunnelling and Field Emission

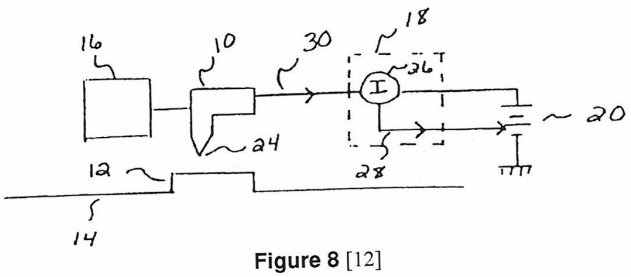


Figure 8 [12]

Use of STM-like System to Measure Node Voltage on Integrated Circuits
A sensing needle (10), which is connected to a supply voltage (20), is positioned directly above a node (12) on an integrated circuit (14). Tunnelling or field emission current is produced in the sensing needle due to the difference in potential between the sensing needle and the node. The system is operated so that the supply voltage is regulated to obtain a fixed current level. Thus, a change in the voltage level to be measured causes an identical change of the supply voltage.

When a probe tip (supplied with a voltage U_2) is held in very close proximity to a conductor (at U_1) a tunnelling current flows, its magnitude depends on the potential difference. For this to occur the size of the probe tip as well as the distance, d, between the tip and the surface have to be as small as fractions of micrometers. For a fixed distance d (i.e. a fixed tunnelling resistance R) the tunnelling current I depends only on the potential difference:

$$I = \frac{(U_2 - U_1)}{R} \qquad (7)$$

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The system shown in Fig. 8 [12] is suitable for tunnel and field emission currents. The expected sensitivity is better than a millivolt. For the detection of a tunnel current the probe-surface distance is about one nanometer. With such a small distance the system may be operated at atmospheric pressure. When the distance d is increased, field emission becomes the dominant process. Then, however, vacuum is necessary. Equ. 7 still holds - with a different value for R. For a sampling operation the electron emission can be triggered by a pulsed laser or particle beam.

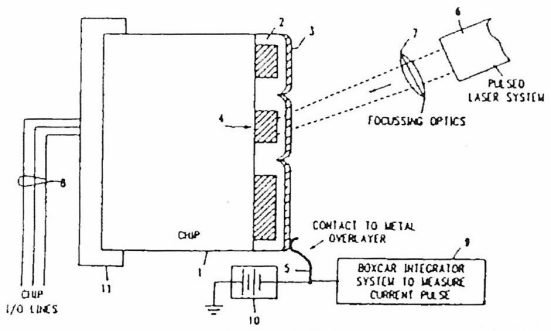


Figure 9 [13]

Noncontact Testing of Integrated Circuits

The metal test pads (4) of an integrated circuit chip-to-test (11) are covered with a photon-transmissive passivation layer (2) susceptible to photon assisted tunnelling which in turn is covered with a thin conductive photon transparent overlayer (3). For the measurement the test pads are accessed through the passivation layer and conductive overlayer by a pulsed laser to provide voltage-modulated photon-assisted electron tunnelling to the conductive overlayer. The conductive overlayer acts as a photoelectron collector for the detector. A chip-to-test which is properly designed for photon assisted tunnelling testing has test sites accessible to laser photons even though passivated.

Laser assisted tunnelling also allows the measurements of voltages in circuits passivated with nonconductive layers up to about 1 µm thick (cf. Fig. 9 [13]). One measures the tunnel current to a transparent conductive overlayer. The passivation layer lowers the threshold energies for electron emission as compared to air. Photon energies of less than 3 eV are sufficient to cause tunnelling when a suitable insulation layer is present.

1.1.5.3 Secondary Electrons

When an object (at potential U_1) is hit by a sufficiently energetic laser or particle beam secondary electrons (with charge e_0) are emitted. Their kinetic energy, T, at an analyser (at potential U_2) is given by:

$$T = T_0 + e_0(U_2 - U_1) \qquad (8)$$

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The emission energy T_0 depends on the work function of the material from which the electrons are emitted and the traversed thickness before emission. An energy analysis of the secondary electrons yields the potential of the emitting object. Variation of the emission energy and field gradients above the circuit tend to limit the sensitivity. This is no serious handicap if only signal levels of either zero or five volts are measured. Secondary electron energy analysers require vacuum chambers.

In a scanning operation the position of the primary beam and the electron signal must be correlated. Depending on the frequency of the signal either real time sampling (up to about 100 MHZ) or stroboscopic sampling is suitable. Commonly the scanning operation is triggered in a predetermined time relation to the voltage signal of interest.

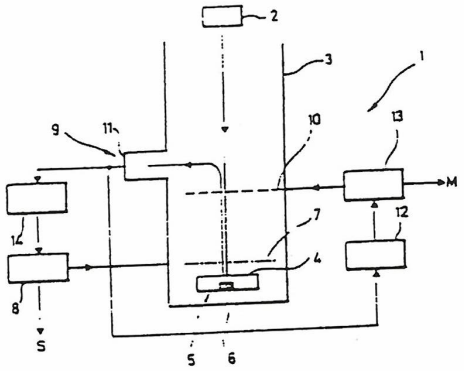


Figure 10 [15]

Contactless Measurement of the Voltage in an Object with an Insulating Surface
A primary electron beam is directed onto the insulating surface (4) of the object (5). The energy of the electrons in the secondary-electron flow generated at the surface of the object is measured and the potential of the conducting zone under the surface is derived. In order to increase the measurement precision, an alternating electrical absorption field is applied above the object and the measurement of the energy of the secondary electrons is carried out in synchronism with the alternating field.

Electron beam testing is the best-established technique. The technology for the required electron beams is known from **S**canning **E**lectron **M**icroscopes (SEM). The range of the electron allows voltage measurements on passivated components covered by thin insulation layers. However, when the beam hits insulating materials, the problem of electrostatic charging arises, and when conductors are hit, signals may be induced in the circuit to be tested. These effects can be minimised by keeping the primary and the secondary electron current equal. For most materials this occurs at electron energies between 0.2 and 3 keV [14]. At these energies the penetration depth is less than 5 µm and the electrons do not reach sensitive parts of the circuit underneath. The amount of possibly hazardous Bremsstrahlung decreases with decreasing electron energy. Typical beam currents are in the nA range. EBT devices provide a voltage resolution of several millivolts (cf. Fig. 10 [15]).

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Particles other than electrons will produce secondary electrons as well. The use of heavier ions offers some advantages. Due to their much shorter penetration depth more energetic beams have to be used which reduces the sensitivity of the primary beam to electric or magnetic stray fields considerably. Ion beams, however, may cause sputtering on the surface of the circuit. This can be used to remove passivation layers to gain access to conducting leads or to repair faults on the circuit. On the other hand thin conductors may be damaged. Appropriate precautions to prevent a damage of the circuitry are necessary [16]. Ion beams (e.g. α-particles) are less commonly used than electron beams.

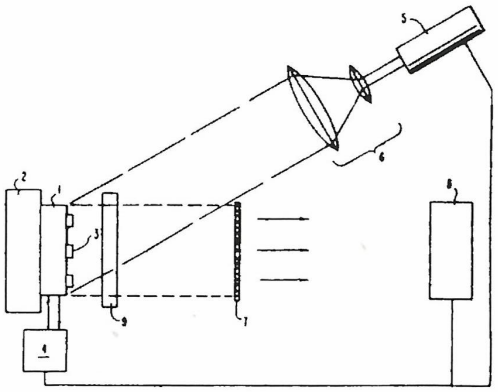


Figure 11 [17]

Full Chip Integrated Circuit Tester

Contactless probing of an integrated circuit is carried out by flooding the surface of the integrated circuit (1) with pulsed ultraviolet laser light, causing photoelectron emission as a function of the potentials at micropoints (3) on the integrated circuit, converting this two-dimensional electron pattern into a corresponding relatively long duration pattern of luminescence by a luminescent target (7), and reviewing the result by video/computer scanning (8). Measurements can be performed either in vacuum or in air, with or without insulating passivation layers present on the chip to monitor instantaneous voltages (logic states and AC switching waveforms) for a full two-dimensional array of micropoints simultaneously.

To generate secondary electrons with a laser beam, photon energies above 4 eV (corresponding to a laser wavelength of less than 300 nm) are necessary. With a sufficiently intense laser it is possible to map the potential distribution over a larger circuit area at once. Such a system is shown in Fig. 11 [17]. With a photo yield of about 10^{-4} electrons per absorbed photon each laser pulse generates about $6 \cdot 10^4$ electrons/μm^2 over a circuit area of 100 mm^2. Appropriate electron optics is required to obtain a distortion-free intensity profile of the secondary electron distribution from which position sensitive electron detectors can recover the two dimensional voltage distribution. Sensitivities of about 1 mV and 5 ps are reported [17].

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1.1.6 Electrometers

Charges of an equal sign repel each other, those of an opposite sign attract each other. The Coulomb force F between two charges q_1 and q_2 at a distance r along the direction of a unit vector e is given by:

$$\vec{F} = -\frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\vec{e} = q_1\vec{E}_2 = \frac{q_1 U}{r}\vec{e} \qquad (9)$$

E_2 is the electric fields originating at q_2 and U the corresponding voltage, ε_0 is the dielectric constant.

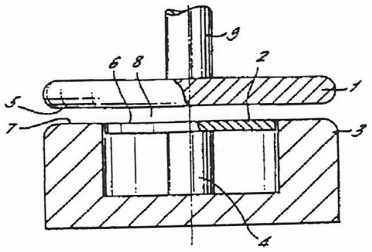


Figure 12 [18]

High Voltage Voltmeter

The high voltage voltmeter, which operates by measuring the electrostatic attraction between two electrodes when a voltage is applied, comprises a high voltage electrode (1), an earth electrode (2) and a guard electrode (3).The attractive force experienced by the earth electrode is measured by a measuring means (4) incorporating e.g. a strain gauge, which gives an electrical signal indicative of the applied voltage. The electrodes are mounted either in vacuum or in a dielectric gas, e.g. sulphur hexafluoride.

When a direct voltage U is applied to a capacitor-like structure, the charge distribution gives rise to a force F between the electrodes. For a parallel plate capacitor ($C=(\varepsilon_0 a)/d$) it can be easily calculated using Equation 9:

$$\vec{F} = q\vec{E} = \frac{C U}{2}\vec{E} = \frac{\varepsilon_0 a}{2}\frac{U^2}{d^2}\vec{e} \qquad (10)$$

where a is the area of one plate and d the distance between the plates. In the Kelvin type electrometers the force is measured with a balance. In the device shown in Fig. 12 [18] a strain gauge is used to measure the force. A voltage of 100 kV gives rise to a force of 3.5 Newtons (d = 10 mm, electrode diameter = 100 mm). Fig. 13 [19] shows a device similar to the gold-leaf electroscope where the force is not measured directly but where the deflection is converted into an optical signal.

More recently microelectromechanical (MEM) components have been employed in electrometers. The device shown in Fig. 14 [20] comprises a 28 microns thick and 2000 microns long cantilever which forms part of a MEM resonator. For a potential difference between 0 and 40 V a (nonlinear) variation of the resonance frequency from 14.5 to 11.5 kHz is observed with this device.

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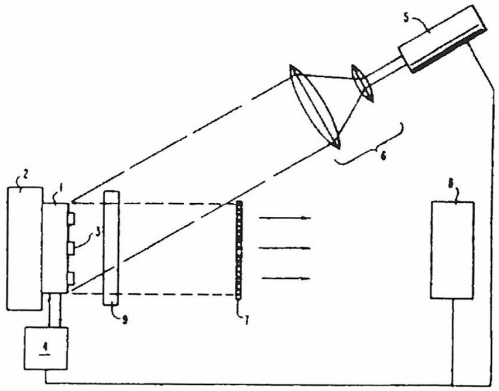


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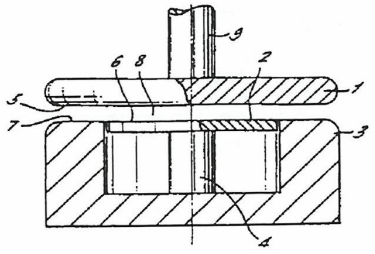


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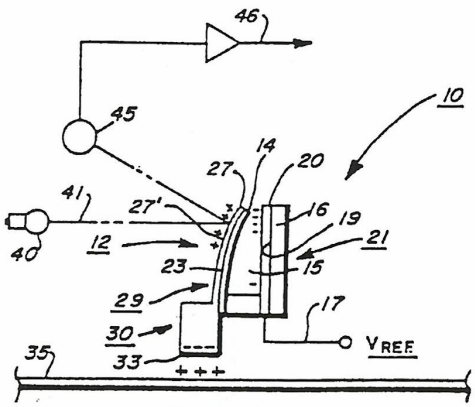


Figure 13 [19]

Electrostatic Voltmeter

An electrostatic voltmeter (10) comprises a microdeflector probe (12) for measuring the charge on a surface (35). The probe comprises a flexible finger (14) cantilevered on a base (16) which is electrically biased to a predetermined potential V_{ref}. A sensing electrode (27) on the finger has a portion (33) which is positioned adjacent to the surface, whereby a charge representative of the charge on the surface is induced on the sensing electrode. The potential difference between the finger and the base causes the finger to deflect. This deflection is converted to a signal representing the charge on the surface by directing a beam (41) of light on the finger and detecting the reflected beam.

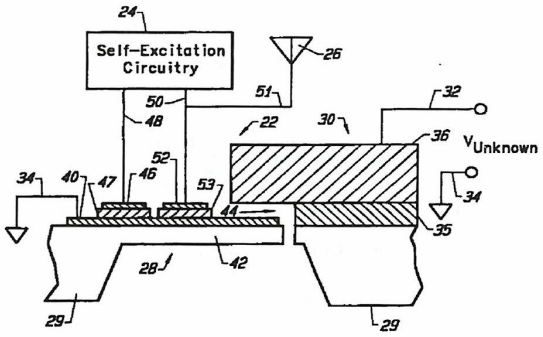


Figure 14 [20]

Microelectromechanical-Based Power Meter

The MEM resonator comprises a cantilever (28) and an associated plate (30). A variable frequency signal from a self-excitation circuitry (24) is applied to an electrode (52) which together with a piezoelectric film (53) and a ground plate (40) forms a drive transducer. A corresponding feedback transducer (46, 47, 50) controls the self-excited oscillation of the cantilever. An electric field across the gap (44) between the cantilever and the associated plate deflects the cantilever and thereby changes its resonance frequency. Output device (26) provides an output representative of the frequency shift. For measurements of line-to-line voltages between powerlines, the cantilever ground plate (40) is connected to a powerline and a conducting plate (36) of the associated plate to an electrode plate located close to the powerline.

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Atomic force microscopes or scanning force microscopes (SFM) are used for high accuracy and high spatial resolution DC voltage measurements on integrated circuits. Since SFMs are less sensible to surface conditions than scanning tunnel microscopes (STM), no special preparation of the surface is required. The force on the conducting SFM tip close to a conducting surface is (in analogy to Equ. 10) proportional to the square of the potential difference. A potential difference $U = U_{DC} + U_{\omega} \sin \omega t$ causes a vibration of the tip with an amplitude A:

$$A \sim U_{DC}^2 + 2\, U_{DC}\, U_{\omega} \sin \omega t + \frac{U_{\omega}^2}{2} (1 - \cos 2\omega t) \qquad (11)$$

For the measurement the tip is biased with an AC voltage having a frequency ω such that the tip will vibrate at the frequency 2ω. If there is a vibration at the frequency ω, it is due to a DC voltage The amplitude of this vibration is proportional to the product of the DC and AC voltages and can be varied by applying a DC bias voltage to the tip. The bias voltage at which the vibration at the frequency ω stops, corresponds to the DC voltage to be determined. An instrument of this type is shown in Fig. 15 [21].

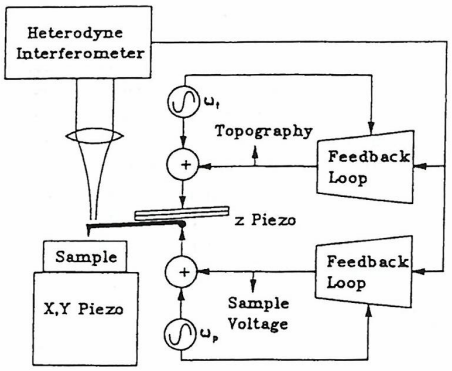


Figure 15 [21]

Potentiometric SFM

Tip vibration is sensed by a heterodyne interferometer and the signal passed to a lock-in amplifier. The lock-in output is a measure of the amplitude of vibration of the tip at ω_p and hence of the DC potential between tip and specimen. The lock-in output is fed back to the tip to obtain zero amplitude of oscillation at ω_p, at which point the DC tip voltage is equal to the voltage on the specimen directly below the tip.

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1.1.7 Electro-Optical Sensors

1.1.7.1 Electro-Optical Phenomena

This section covers sensors whose optical properties change in response to electric fields. The sensors currently used are based on one of the following effects:

- the linear electro-optic effect - Pockels cells
- the quadratic electro-optic effect - Kerr cells
- change of optical transmissivity due to excitonic electroabsorption - multiple quantum well devices (MQW)
- change of optical transmissivity due to variations of the alignment of liquid crystals (LC), the Franz-Keldysh effect or electrochromism.

Electric fields give rise to linear birefringence in some materials. This phenomenon is called the electro-optic effect. Linear birefringence of a material causes different components of polarised light to travel at different speeds. Field measurements with Kerr and Pockels cells consist of the detection of the resulting phase shift between the different components and the corresponding change of polarisation. Measurements of the changes in optical absorption or transmissivity are easier to perform. The field of application of related sensors is, however, rather restricted.

The Kerr effect is observed in liquids of polar molecules; the Pockels effect in some non-centro-symmetric crystals. In Kerr cells a phase shift is induced between the components with a polarisation parallel and perpendicular to the electric field, thus, the electric field has to be perpendicular to the direction of propagation of the light. In Pockels cells the electric field can be parallel or perpendicular to the direction of propagation of the light. Due to the tensor character of the Pockels effect, the phase shifts depend on the direction of the light and the orientation of the polarisation vector with respect to the crystal axes. Their linear response to the electric field makes Pockels cells more suitable for lower fields as compared to Kerr cells. The relatively large phase shifts can be observed with simple analysers, so that usually sophisticated interferometers are not required.

1.1.7.2 Pockels Cells

In general the tensor of the Pockels effects has 18 non-zero coefficients. In some highly symmetric crystals only three are non-zero, in uniaxial crystals they are different whereas in cubic crystals they are identical. $Bi_{12}SiO_{20}$ (BSO), $Bi_{12}GeO_{20}$ (BGO) and $Bi_4Ge_3O_{12}$ are not birefringent in the absence of a field, $NH_4H_2PO_4$ (ADP), KH_2PO_4 (KDP), $LiNbO_3$, $LiTaO_3$ and quartz exhibit natural birefringence. The relation between the electrical field strength E and the phase shift δ is given by:

$$\delta = \frac{2\pi}{\lambda} \ell \, n_0^3 \, r \, E \qquad (12)$$

where λ is the wavelength of the incident light (e.g. 1 µm), n_0 the index of refraction of the Pockels crystal (1.5 for KDP), r its electro-optic coefficient ($r \sim 25 \cdot 10^{-12}$ m/V for KDP [1]) and ℓ the length of the cell (e.g. 10 mm). With these parameters an electric field of $3 \cdot 10^5$ V/m causes a phase shift of $\pi/2$. The measuring system consists of: a laser light source, a polariser (to polarise the light at an angle of -45° with respect to the crystallographic axis of the crystal), the crystal and an analyser at an angle θ with respect to the axis.
A $\lambda/4$ plate somewhere between the polariser and analyser provides an additional phase shift of $\pi/2$.

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The intensity I of the light leaving the analyser is given by [24]:

$$I = \frac{I_0}{2} (1 + \sin 2\theta \cdot \sin \delta) \quad (13)$$

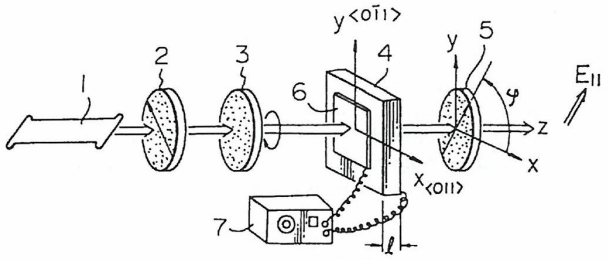


Figure 16 [22]

Pockels Cell Voltage and Electric Field Measuring Device

The device includes a polariser (2), a quarter-wave plate (3), an electro-optic crystal (4) consisting of a material having an optical rotatory power, and an analyser (5). The angle of orientation φ of the analyser, relative to the optical axis of the crystal, is set to the product of θ and ℓ, where θ represents the optical rotatory power of the crystal near the centre of the temperature range at the installation environment and ℓ represents the thickness of the crystal. The specified relation between φ and θ·ℓ maximises the temperature stability of the device by ensuring that the sensitivity of the device is substantially independent of temperature.

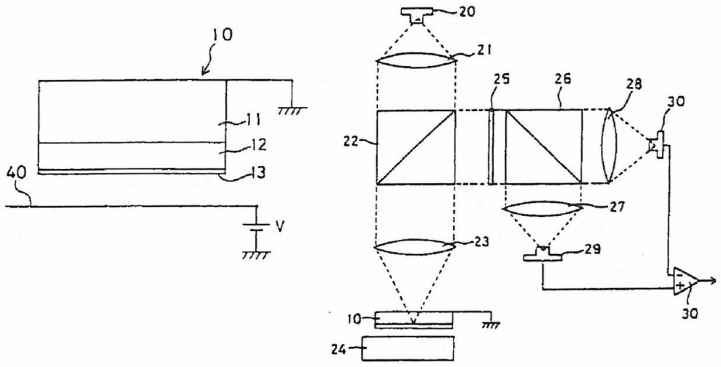


Figure 17 [23]

Potential Sensor Using an Electro-Optical Crystal

The monolithic sensor (10) consists of a high-resistance (>10^5 ohms cm) compound semiconductor (12) which is grown on a low-resistance (<10^{-1} ohms cm) compound semiconductor (11) and covered by a reflecting dielectric film (13). The lattice constants and the thermal expansion coefficient of the semiconductors (11, 12) are similar. Their large band gaps allow the use of light of a short wavelength such that a high sensitivity can be achieved. Linearly polarized light from the laser diode (20) is directed onto the sensor, whose anisotropy depends on the potential applied to the object of measurement (24). The reflected light is deflected by the half-mirror (22) through half-wave plate (25) to the beam splitter (28) from where it is directed into light receiving elements (29, 30).

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With an angle θ of +45° or -45° (the orientation of the analyser being perpendicular or parallel to the polariser) one obtains the maximum intensity variation. The sensor is mounted between two electrodes and is suited to measure one component of the electric field, cf. Figure 16 [22]. Figure 17 [23] shows a probe for integrated circuits with a Pockels cell: the probe structure (left) and the apparatus (right).

An ellipsoidal crystal Pockels sensor which is traversed by three light beams with appropriate directions of propagation and polarisations is suitable to detect all three field components [24]. For such a detector the crystallographic symmetry of the sensing element can be either uniaxial 622, 422 or $\bar{4}2m$, or cubic $\bar{4}3m$ or 23. The three perpendicular axes of the ellipsoid are directed along the three orthogonal crystallographic axes of the highest crystal symmetry. In each measurement channel a light beam from a monochromatic light source is polarised along a respective crystallographic direction, reflected at the opposite end of the crystal, analysed and detected. The spherical shape of the sensor minimises the distortion of the electric field. If multimode polarisation conserving fibres are used, polariser and analyser can be at a remote position. The reflection of the beam at one end of the sensor doubles the effective length of the sensor and leads to the cancellation of some of the distortions.

Pockels cells are commonly employed for a wide range of applications, from probes for integrated circuits to high voltage measurements. They can be used for frequencies up to above one GHz. Because of their thermal sensitivity, temperature compensation may be necessary.

1.1.7.3 Kerr Cells

Kerr cells have long been employed for measurements of high voltages and high voltage pulses. Polar liquids like benzene, water, acetone, chlorobenzene and nitrobenzene are commonly used in these cells. The phase difference d between light polarised parallel and perpendicular to the electric field E is:

$$\delta = 2 \pi \ell b E^2 \qquad (14)$$

where b is the (temperature dependent) Kerr constant (e.g. $b \approx 10^{-12}$ m V^{-2} for nitrobenzene [1]), ℓ the length of the cell (e.g. 50 mm). An electric field of $3 \cdot 10^6$ V/m causes a phase shift of about π. An experimental set-up is shown in Fig. 18 [25]. A laser beam is polarised at -45°with respect to the electric field, passes the Kerr cell and an analyser at 90° with respect to the polariser. The intensity at the output of the crossed polariser/analyser as a function of the phase shift and the maximum intensity I_o is:

$$I = I_0 \sin^2 \frac{\delta}{2} \qquad (15)$$

Typical applications of Kerr cells cover electrical fields in the range 10^5 to 10^7 V/m, the frequency response is linear up to about 100 MHZ [26]. Many materials used for Kerr cells also exhibit the Cotton-Mouton effect (cf. Section 1.2.9).

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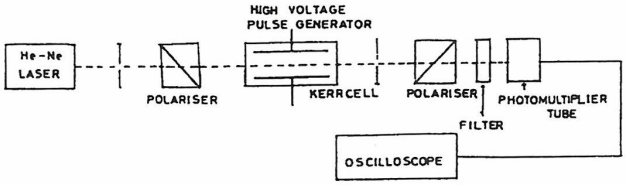


Figure 18 [25]

Arrangement with a Kerr Cell

1.1.7.4 Multiple Quantum Wells

A more recent electro-optic sensor is based on the change of the optical transmittivity of a "semi-insulating" multiple quantum well (MQW) structure for photons, cf. Fig. 19 [27]. It comprises a semiconductor material with $\rho > 10^6$ ohm cm. For photons with an energy corresponding to the energy of excitonic absorption, this material has a fixed transmittivity (T_1) in a given bias field. An additional field leads to a broadening of the absorption peak and therefore results in a change in transmittivity (from T_1 to T_2).

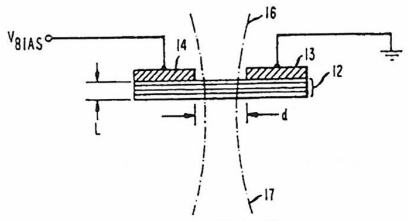


Figure 19 [27]

Electrooptic Apparatus for the Measurement of Ultrashort Electrical Signals

Coplanar striplines (13, 14) are fabricated on the MQW structure (12). When an electrical signal is applied to the striplines, a perturbed field ($E_{bias} + E_{signal}$) is generated and leads to a broadening of the excitonic absorption peak. The modulation of the transmitted photon beam images the applied electrical field E_{signal}.

1.1.7.5 Other Absorption Effects

Several effects lead to field dependent changes of the optical transmissivity of certain materials. Most of these effects occur only in a narrow field range where they show a strong field dependence. Therefore they are often employed for binary sensors (comparators) to detect whether a voltage exceeds a certain threshold. Liquid crystals are the most common devices of this type.

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Nematic liquid crystals show several electro-optic effects. In the nematic phase the molecules are still arranged in (already broken) layers. The field dependent deformation of aligned phases (DAP effect) is employed for most analogue field measurements. It causes a decrease in transmissivity proportional to the applied field. For a 10 µm thick cell this occurs between 1.5 and 5 volts [1]. The response time is in the order of several microseconds. Figure 20 [28] shows an application of a liquid crystal cell for voltage measurements.

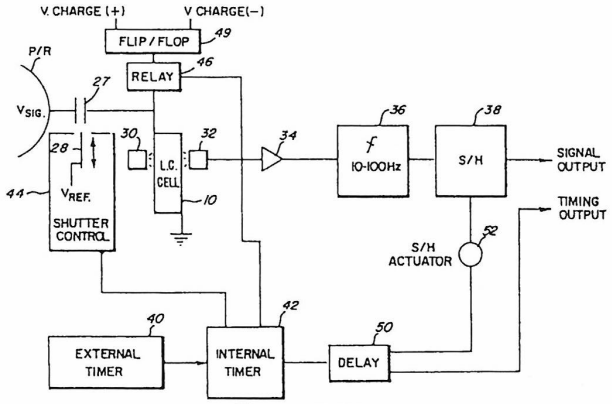


Figure 20 [28]

Liquid Crystal Voltmeter

The device comprises a liquid crystal cell (10) electrically connected to a charged surface and having a light transmissivity varying with applied voltage. Light from a light source (30) is directed through the liquid crystal cell to a light detector (32) which detects changes in the intensity of light. A saturation level biasing voltage is periodically applied to the liquid crystal cell to set the cell to a reference level to clear the cell of transient polarization effects.

The Franz-Keldysh effect causes in certain semiconductors a field dependent shift of the optical absorption band edge to lower energies. Fields of about 1 kV/mm lead to a measurable decrease of the transmissivity for light with an energy less than the band gap of the semiconductor. For CdS and ZnS absorption occurs at wavelengths of 500 and 300 nm respectively. Figure 21 [29] shows a device based on this effect.

Electrochromic materials change colour when a DC potential is applied. This change in light absorption is due to a change of oxidation state of the material (thus electrochromic materials strictly speaking are not contactless sensors because they require an electric connection). Solids like WO_3 or aqueous mixtures of potassium tungstate are electrochromic. A list of other suitable materials is given in [30]. For voltage measurements µm thin films or cells of these materials are mounted between two electrodes. They change colour at voltages close to one volt and it takes about a second (the time scale of redox reactions) for the colour to change. The life time of such a sensor is limited to several hundred colour changes.

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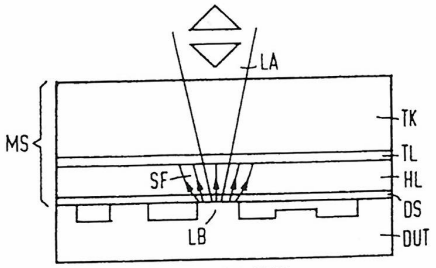


Figure 21 [29]

Method for Optically Measuring Electrical Potentials

A laser probe beam (LA) is directed onto a point (LB) at which the potential is to be measured. The measuring sensor (MS) has a carrier crystal (TK) which is transparent for the laser beam (LA) and which carries a transparent conductive layer (TL) and a mirrored dielectric semiconductor (HL), the light absorption characteristic of which is varied in dependence on the stray electrical field from the electrical potential at the point (LB).

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1.1.8 Piezoelectric and Electrostrictive Materials

1.1.8.1 Measuring the Deformation

Piezoelectric crystals become polarized when they are deformed, and a charge and an associated electric field build up. This behaviour is called the piezoelectric effect. The reverse piezoelectric effect causes a piezoelectric crystal to deform when exposed to an electric field. Depending on whether the electric field and the deformation are parallel or mutually perpendicular, one speaks of a longitudinal and a transverse effect. The relative deformation, $\Delta L/L$, is a linear function of the applied electric field, E, and the piezoelectric coefficient, d, for the respective crystal orientation:

$$\frac{\Delta L}{L} = d\,E \tag{16}$$

For piezoelectric ceramics (PZT) d is about $0.5 \cdot 10^{-9}$ m/V [31].

A more recent approach to field measurements employs electrostriction instead of the inverse piezoelectric effect. An applied electric field, E, induces a strain in electrostrictive ceramics which causes a deformation, $\Delta L/L$. The deformation is proportional to the square of the field strength and to an effective electrostrictive coefficient, M:

$$\frac{\Delta L}{L} = M\,E^2 \tag{17}$$

For Ba : PZT the value of M is about 10^{-16} $(m/V)^2$ [32].

A simple sensor with these materials consists of a first piezoelectric or electrostrictive material to which the voltage to be measured is applied and which transmits the resulting mechanical waves to a second piezoelectric crystal which reconverts them into a voltage, cf. Figure 22 [33]. In this reference it is suggested to use as first material an electrostrictive material in order to prevent ageing and the risk of depolarisation of the material in high electric fields and also to reduce the size of the sensor.

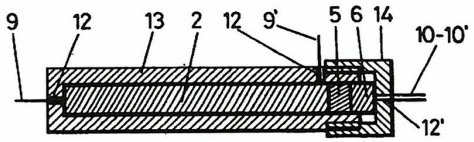


Figure 22 [33]

Voltage Transformer Based on Mechanical Waves

The primary voltage is applied through two electrodes (9, 9') to a first piezoelectric or electrostricive material (2) acting as transmitter. The transmitter is coupled via a dielectric body (5) to the second piezoelectric material (6) acting as receiver and providing the output voltage on two electrodes (10, 10'). The housing consists of a tube (13) with a cover (14) to adjust the pressure on the sensor elements.

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Various other techniques can be employed for electric field measurements with piezoelectric or electrostrictive materials. The most common way is to bond an optical fibre to the material. The change of the length of the fibre causes a phase shift in the transmitted light that can be measured with an interferometer. The phase shift depends on ΔL, the wavelength of the light, λ, the refraction index of the fibre, n, and a factor, f, that accounts for the coupling between the sensor and the fibre:

$$\delta = \frac{2\pi}{\lambda} n f \Delta L \qquad (18)$$

Since for the measurement of magnetostriction similar methods are employed, reference is also made to Section 1.2.10.

1.1.8.2 Piezoelectric Crystals with Optical Fibres

This type of sensor consists of a piezoelectric crystal with an optical fibre bonded to it. To measure e.g. a voltage in a gas-insulated power appliance, the sensor is positioned somewhere between the conductor and the housing and the orientation of the crystal is chosen such that it senses the electric field associated with the voltage between conductor and housing. The phase shift induced by an electric field of 100 V/m can be derived from Equs. 16 and 18 to about 0.004 radians for a 1 cm sensor and a 1 µm laser.

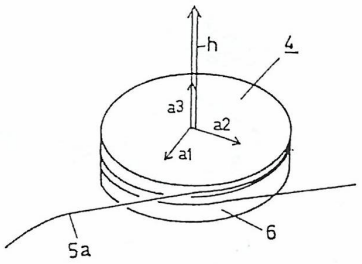


Figure 23 [34]

Optical-fibre Sensor

The sensor for measuring a particular directional component of an electrical field comprises a piezoelectric body (4) and a glass fibre (5a) which is rigidly connected to the piezoelectric body in a given length section. A crystal class and a crystallographic orientation of the piezoelectric body is selected such that only the directional component of the electrical field which is parallel to a given body axis (h) of the piezoelectric body causes a change in a length of the glass fibre by means of an inverse piezoelectric effect. The change in length is measured interferometrically.

Simple polariser/analyser arrangements will not suffice to determine phase shifts of this magnitude accurately. Usually interferometers of the Mach-Zehnder, Fabry-Perot or two-mode [31] type are used. In the Mach-Zehnder arrangement coherent light from a laser is sent through two single-mode fibres where the first one is bonded to the piezoelectric crystal and the second one serves as reference. In a two-mode interferometer one needs only one dual-mode fibre. The two modes undergo different phase shifts. An additional modulator (e.g. a piezoelectric crystal) serves to adjust the working point, i.e. to set the phase shift in the absence of a field (to e.g. $\pi/2$).

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With the homodyne detection technique one compensates the phase shift due to the electric field and the result is obtained from the magnitude of the compensating variable. In Mach-Zehnder interferometers the compensation can be done either on the reference or the measurement path, in the two-mode interferometer it is done in the measurement path. Because of the temperature dependence of the length variation, measuring and compensating elements should be at a similar temperature.

The choice of the crystal depends on the application, e.g. whether one wants to employ the parallel or the transverse effect. Fig. 23 [34] shows a disk-shaped sensor. To increase the observed phase shift one simply has to wind the fibre a couple of extra times around the sensor. Though this is true for all sensors, it is more obvious for disk-shaped ones. Tables about crystal classes suitable for different sensor geometries are given in [34]. For the disk-shapes, polyvenylidenfluorid (PVDF), piezoelectric ceramics Lithiumniobat and quartz are appropriate.

A special class of crystals, like, e.g. GaAs, allows the simultaneous measurement of all three components of the electric field [35]. For some of these crystals the sensitivities differ according to the orientation.

1.1.8.3 Piezoelectric Electroacoustic Sensors

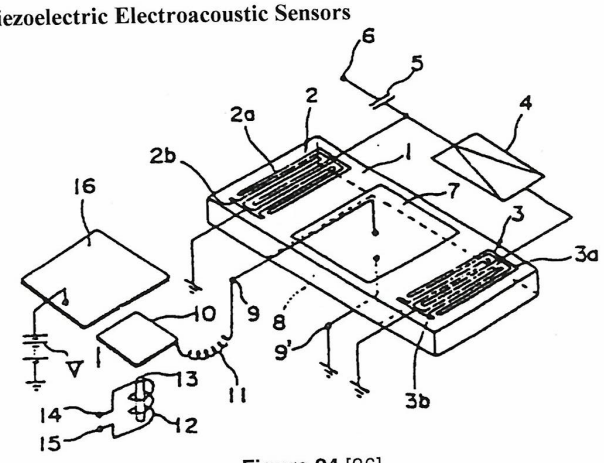


Figure 24 [36]

Electrostatic Voltage Sensor

The sensor includes a surface acoustic wave oscillator with a surface acoustic wave propagating medium (1) and transmitting and receiving transducers (2,3) coupled to the medium. A voltage collection member (10) vibrated with a constant frequency faces the charging plate (16) to be measured. The oscillating signal is applied to the electrode (7) and thereby causes a variation of the surface acoustic wave delay. Voltage is measured through the resulting variation of the oscillation frequency which is obtained at the terminal (6).

Piezoelectric electroacoustic sensors transform an electric field into a change of the resonance frequency of an oscillator. Such an oscillator comprises a transmitter and a receiver mounted spaced apart on a piezoelectric plate and connected by a feedback line. Any length variation, $\Delta L/L$, of the piezoelectric material (e.g. $MgNbTiZrPbO_3$ or $LiNbO_3$), which acts as delay means for surface acoustic waves, leads to a frequency variation, $\Delta f/f$. A device based on surface acoustic waves (SAW) is shown in Fig. 24 [36].

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To avoid problems that arise when a piezoelectric element is exposed to a DC field for a longer time (creep phenomenon), the DC voltage is modulated before being applied to the sensor. The circuitry to evaluate the frequency changes from the frequency modulated resonance signal may incorporate means to compensate for temperature drift. Over a voltage range from -1 kV to +1 kV a linear response of about 1V/kV has been observed [36].

A more recent approach is based on Lamb waves that propagate within the sensor plate. For this purpose transmitter and receiver electrodes have counter-plate earth electrodes on the reverse side of the sensor plate. Fig. 25 [37] shows an example of the response of this type of sensor at different resonance frequencies.

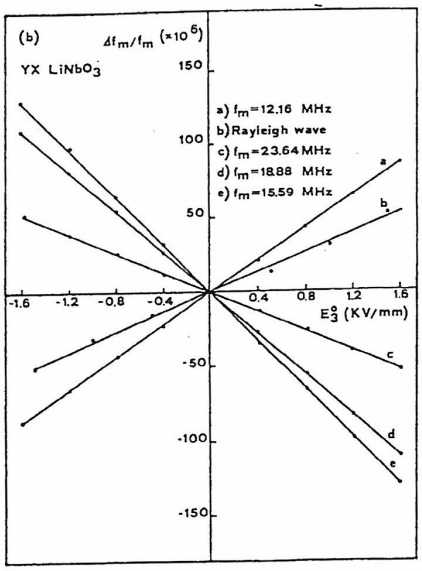


Figure 25 [37]

Fractional frequency changes as a function of the applied electric field for a selected number of Lamb modes and for the Rayleigh (surface) wave propagating in YX $LiNbO_3$ plates.

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1.1.8.4 Electrostrictive Sensors

The quadratic field dependence of the electrostrictive effect allows the amplification and frequency shifting of the signal to be measured when a DC and one or more AC fields [32], [38] are superimposed. When the electrical field $E = E_{DC} + E_\omega \cos \omega t + E_\Omega \cos \Omega t$ is squared, a DC term and frequency mixed terms with frequencies Ω, ω, $\omega \pm \Omega$, 2Ω and 2ω arise and cause length variations at these frequencies, e.g.

$$\left(\frac{\Delta L}{L}\right)_\omega = 2\, M\, E_{DC}\, E_\omega \cos \omega\, t \qquad (19)$$

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Measurements of low frequency, Ω, fields with piezoelectric materials suffer from a noise spectrum with a 1/f characteristic. In order avoid this noise one applies a high frequency electric field, E_ω, and measures the phase shift at $\omega \pm \Omega$. Figure 26 [32] shows the strain on the crystal at the frequencies $\omega \pm \Omega$ as a function of the carrier amplitude E_ω. The other application is the measurement of weak fields. According to Equation 19 the phase shift can be amplified by a strong DC or AC bias field.

With an optical fiber attached to a 150 mm crystal, a 1µm laser and fields of 10^4 V/m and 100 V/m a phase shift of about $3 \cdot 10^{-4}$ radians can be expected. The analysis of the phase shift is done with interferometers as for piezoelectric crystals.

In an investigation [38] of two materials that exhibit the electrostrictive effect, barium-doped lead zirconate titanate (Ba :PZT) and a lead magnesium niobate/lead titanate(PMN)-based ferroelectric relaxor, a (frequency dependent) resolution of 1nV/√Hz for 15 cm of fiber has been observed with PMN.

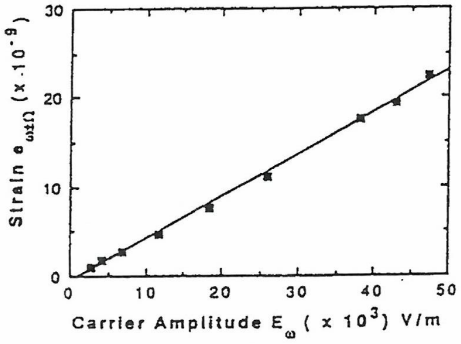


Figure 26 [32]

Dependency of the strain $e_{\omega\pm\Omega}$ on the dither amplitude E_ω for E_Ω = 1000 V/m

1.2 CURRENT SENSORS

1.2.1 Principles

The most fundamental way to measure an electrical current is based on its very definition, i.e. the movement of charge carriers. One "simply" counts the number of charge carriers per unit time. This method is used for currents of charged particle beams (an application not covered by this book), e.g. with a Faraday cup. In most applications, however, one is concerned with much higher currents in conductors, e.g. wires, where one wants to measure currents without interrupting them.

In the same way as voltage measurements can be performed as current measurements, current measurements can be performed as voltage measurements. Ohm's law gives the relation between the current flowing through a resistor (of known resistance) and the resulting voltage drop. This method is mainly used for high currents (Sect. 1.2.3) and in computerised measuring systems with ADCs.

The oldest method to measure direct current exploits the Lorentz force, i.e. the force acting on charged particles in a magnetic field (Section 1.2.6). Electric currents give rise to magnetic fields on their own such that most magnetic field sensors can be used as current sensors. The sensors described in Sections 1.2.7 to Section 1.2.13 respond to the magnetic field, i.e. to different field related phenomena. Hall elements (Section 1.2.7) and semiconductor magnetoresistances (Section 1.2.8) sense the Lorentz force. With magnetooptical and magnetostrictive sensors changes of optical properties or of the dimension of the sensors are observed (Sections 1.2.9 and 1.2.10). Magnetic resonance probes (Section 1.2.11) respond to the field dependent energy splitting of electron or nuclear energy levels. SQUIDS (Section 1.2.12) sense the magnetic flux. Section 1.2.13 covers various other magnetic field sensors like ferromagnetic sensors that are magnetised by magnetic fields and where this magnetisation leads to different observable effects. Alternating magnetic fields due to alternating currents cause variations of the magnetic flux. Inductive sensors, e.g. coils with or without magnetic cores, are described in Section 1.2.14.

The use of SI units leads to a minor inconvenience when dealing with magnetic fields. Magnetic fields are represented by the field vector H, its dimension is A/m. Some equations, however, are expressed in terms of the magnetic flux density B, given in Tesla, 1 T = 1 V s m^{-2} (the conversion to Gaussian CGS units is as follows: 1 A/m = $4\pi \cdot 10^{-3}$ Oe and 1 T = 10^4 G). Whereas in the Gaussian CGS system B and H are identical in vacuum, in the SI system they are related through the vacuum magnetic permeability μ_o ($\mu_o = 4\pi \cdot 10^{-7}$ Vs/Am):

$$\vec{B} = \mu_o \vec{H} \qquad (20)$$

Because of the identity of B and H in vacuum in the Gaussian CGS system, also B is frequently referred to as magnetic field. For magnetic field responsive current sensors the external magnetic field due to the current to be measured is the primary input. Therefore all magnetic flux densities cited in this text refer, unless explicitly otherwise stated, to the vacuum magnetic flux density, which is related to the magnetic field through equation 20.

The relation between an electric current I and the resulting magnetic field is given by Maxwell's equations. The line integral of the magnetic field H along a path s that encloses a conductor carrying a current I is:

$$\oint \vec{H}\, d\vec{s} = I \qquad (21)$$

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The strength of the magnetic field at a distance r from a conductor is:

$$H = \frac{I}{2\pi r} \tag{22}$$

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Inside a coil with n windings per length ℓ that carry a current I, the magnetic field is given by:

$$H = \frac{n}{\ell} I \tag{23}$$

When a magnetic material is placed in a magnetic field H, it becomes magnetised with a magnetisation M:

$$M = (\mu - 1) H = \chi H \tag{24}$$

where $\mu = (M + H)/H$ is the magnetic permeability and $\chi = \mu - 1$ the magnetic susceptibility. Ferromagnetic materials have high susceptibilities χ (e.g. Fe $\approx 10^4$). χ is much smaller for paramagnetic ($\chi > 0$) and ($\chi < 0$) diamagnetic substances. Susceptibility and the permeability of ferromagnetic materials depend on both the field strength and previous magnetisation (hysteresis). The relation between M and H is linear only at lower magnetic fields, at higher field strengths M saturates. Because of this most current sensors that use ferromagnetic cores are operated as zero field detectors, i.e. as current comparators. A feedback circuit provides a compensating current to cancel the magnetic field.

When a ferromagnetic substance is exposed to a magnetic field H, the resulting magnetic flux density B_m inside the material exceeds B_o, the value in the vacuum. This is due to the magnetisation of the substance. The enhancement corresponds to the permeability μ:

$$\vec{B}_m = \mu_o (\vec{H} + \vec{M}) = \mu_o \mu \vec{H} = \mu \vec{B}_o \tag{25}$$

Another important quantity in this context is the magnetic flux, Φ. The variation of the magnetic flux is mainly used in the context of induction (Section 1.2.14). The flux is defined as the integral of the magnetic flux density B over a surface S, e.g. the area enclosed by the winding of a coil:

$$\Phi = \int_S \vec{B}\, d\vec{a} \tag{26}$$

The unit for the flux is Weber (Wb), 1 Wb = 1 Vs.

In various applications a sensor is placed in a gap of an annular magnetic core that surrounds a current carrying conductor to enhance the magnetic field at the sensor. Because of the flux conservation the magnetic field in the gap, H_g, of an annular core (magnetic permeability μ, radius r, gap width d) is:

$$H_g = \frac{\mu I}{d(\mu - 1) + 2\pi r} \tag{27}$$

Cf. page 150

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There are two asymptotic cases, in both cases H_g is greater than the field in the absence of the magnetic core (cf. Equation 22):

- $d << r/\mu$, the second term in the denominator of Equation 27 dominates and the field in the gap is amplified by a factor μ;
- $d\,\mu >> r$ (for highly permeable iron cores μ is > 1000), the first term in the denominator dominates and the magnetic field is amplified by a factor $2\pi \cdot r/d$.

One advantage of magnetic cores arises from the fact that external magnetic fields cancel in the integral around the closed loop (cf. Equation 21). When weak currents are to be measured, either form of amplification or shielding is mandatory to eliminate the influence of the earth's magnetic field (about 20 A/m). At strong magnetic fields, however, saturation of the core occurs.

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1.2.2 Charge Integration

To perform a simple current measurement by charge integration, one can monitor the slope of the voltage across a capacitor while it is charged or discharged by the current to be measured. In the circuit shown in Figure 27 [39] the collected charge is used to control a transistor.

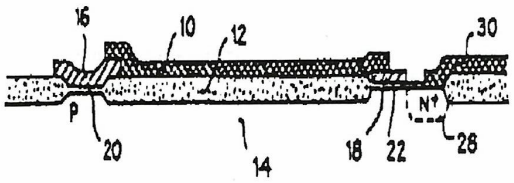


Figure 27 [39]

Measuring Device for very Low Currents

Electric charges, the flux of which constitues the current to be measured, are collected on the conducting electrode (10) which is connected to the insulateed gate (16) of a FET and a conducting layer (18). The charges on the electrode are compensated by the injection of charge carriers from the semiconducting zone (14) through a thin insulating layer (22). This is done by accelerating the charge carriers in the semiconducting zone (14) such that they can pass the insulating layer (22). The frequency and the duration of the accelerating periods depends on the current through the FET.

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1.2.3 Shunts

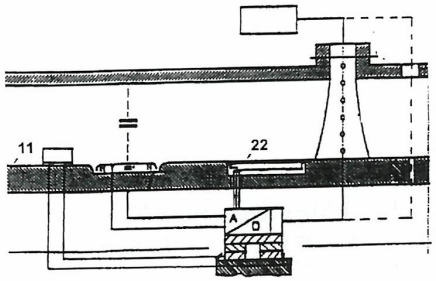


Figure 28 [40]

Current Transformer

For the measurement of transient, rapidly varying short-circuit currents, etc., in particular in gas-insulated, metal-encapsulated switch-gear a current transformer is mounted in at least one power line (11). The current transformer has a length of thin-walled tubing (22) which conducts transient short-circuit currents occurring in the power line (11) and whose external diameter is equal to the external diameter of the power line (11). The voltage drop along a line at the surface of the length of tubing (22) is used as a measure of the transient short-circuit current.

It is a well-known technique to determine the (high) current that flows through a conductor from a measurement of the voltage drop across a resistor (current shunt). However, at high frequencies the thickness of the shunt is crucial: its resistance corresponds to the ohmic resistance only if its thickness is equal to or less than the penetration depth (skin effect). In the example shown in Fig. 28 [40], the current on a power line is determined from the voltage drop across a thin tubing.

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1.2.4 Calorimetric Methods

These methods are in fact based on power measurements. We have included them in the section dealing with current sensors because they require a current to flow. When an electric current, I, passes through a conductor with resistance R some power, P, is dissipated:

$$P = R I^2 = \frac{U^2}{R} \tag{28}$$

The resulting temperature rise of the conductor can be measured with any suitable temperature sensor and be used to determine either U or I. The response time of corresponding sensors crucially depends on the size and the thermal properties of the conductor and the coupling of the conductor to the sensor. An application in which the sensor immediatly responds to temperature changes of the conductor is the measurement of infrared radiation from power transmission lines, cf. Figure 29 [41].

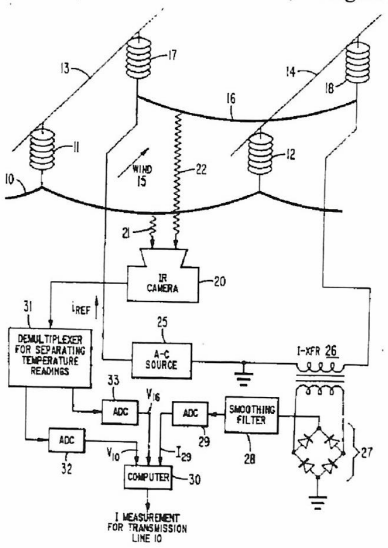


Figure 29 [41]

Measurement of the Current Flow in an Electric Power Transmission Line

The construction of a high-tension line with counterwound helical conductors around a supporting core minimizes the surrounding magnetic field and thus reduces the skin resistance of the line as compared to its bulk resistance . Infrared radiation from the I^2R losses in the line is thus linearized and the current in the line can be directly measured by sensing the infrared radiation from the line using using infrared detectors. Radiation from a hot line (10) and a reference line (16) is compared. A current of about 1000 (100) A leads to a heating of 45 (0.45) °C of a 220 V line at 35 °C exposed to a cooling cross wind in the example given. The cited resolution of the infrared cameras is 0.05 - 0.5 °C.

In another approach a sensing material which exhibits an observable temperature dependent effect is either placed next to the current carrying conductor or used as conductor. If the observable effect occurs at a given threshold temperature, a tapered conductor (i.e. a conductor with a smoothly varying resistance along the current path) can be used to provide an analog indication over a predetermined current range. If the observable effect is irreversible, the sensor acts as maximum sensor.

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